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# Sintering and Fracture Behavior of Plasma-Sprayed Thermal Barrier Coatings

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Thermal barrier coatings will be more aggressively designed to protect gas turbine engine hot-section components in order to meet future engine higher fuel efficiency and lower emission goals. There is a need to characterize the fundamental sintering and fracture behavior of the current $ZrO_2$-(7~8)wt%$Y_2O_3$ coating, in order to fully take advantage of the coating capability. In addition, a thorough evaluation of the coating behavior and temperature limits will be useful for more accurately assessing the benefit gained from future advanced coating systems.

In this study, the sintering behavior of plasma-sprayed $ZrO_2$-8wt%$Y_2O_3$ coatings was systematically investigated as a function of temperature and time using a dilatometer in the temperature range of 1200-1500°C. The coating sintering kinetics obtained by dilatometry were compared with the coating thermal conductivity increase kinetics, determined by a steady-state laser heat-flux testing approach, under high temperature and thermal gradient sintering conditions. The mode I, mode II, and mixed mode I-mode II fracture behavior of as-processed and sintering-annealed coatings was determined in asymmetric flexure loading at ambient and elevated temperatures in order to evaluate the coating sintering effects on the fracture envelope of $K_I$ versus $K_{II}$. The coating thermal conductivity cyclic response associated with the interface delamination of the coating systems under simulated engine heat-flux conditions will be discussed in conjunction with the sintering and fracture testing results.

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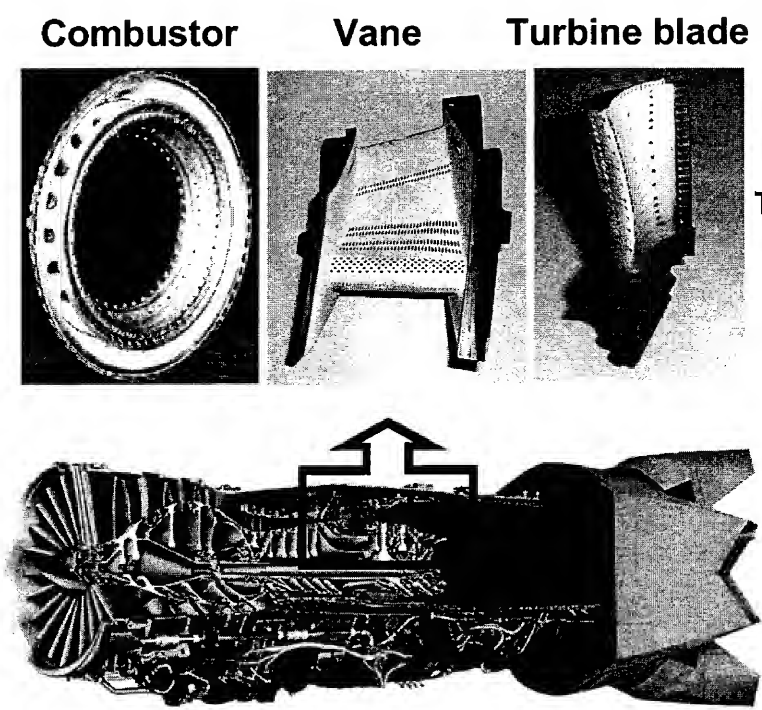
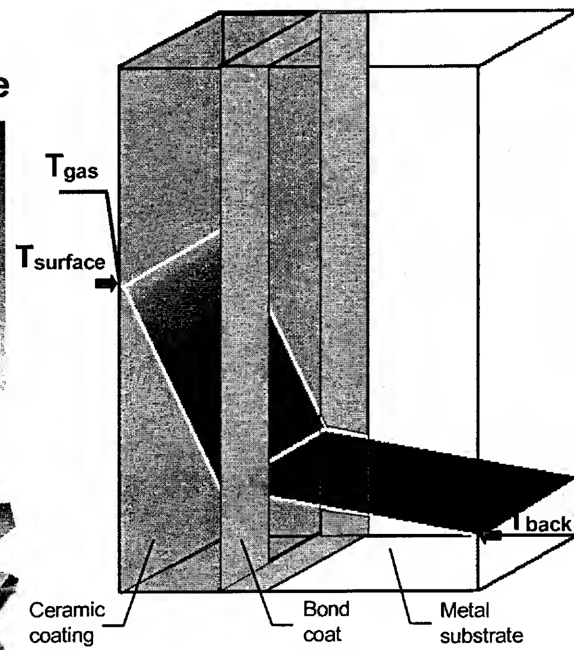
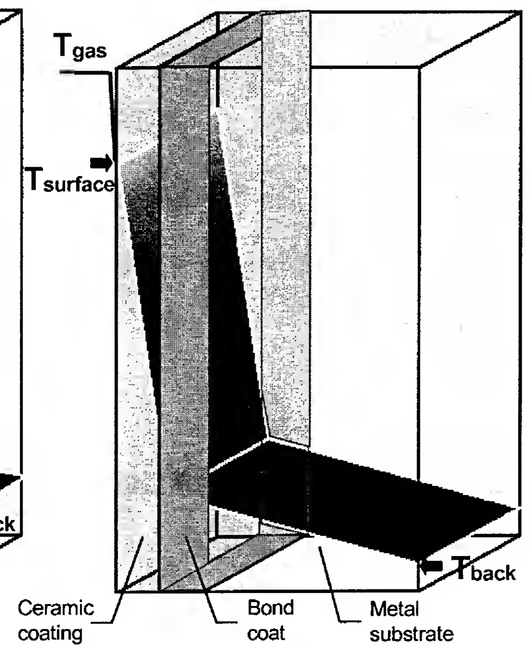
# Motivation

- — Thermal barrier coatings (TBCs) are currently used in turbine engines to protect hot-section components
- — TBCs will be more aggressively designed to increase engine temperatures, reduce cooling requirements, and improve engine fuel efficiency and reliability
- — Coatings sintering and durability issues are of concern




(a) Current TBCs




(b) Advanced TBCs

# Objectives

- **The sintering behavior of plasma-sprayed $ZrO_2$-8wt%$Y_2O_3$**
  - Sintering shrinkage strains and rates
- **Sintering induced conductivity Increases of plasma-sprayed $ZrO_2$-8wt%$Y_2O_3$ as a function of temperature**
  - Comparisons with some of more advanced TBCs
- **Effect of sintering on strength and fracture behavior of plasma-sprayed $ZrO_2$-8wt%$Y_2O_3$ coatings**
  - Strength, fracture toughness and other mechanical properties

# Experimental

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— Material: Plasma-sprayed $ZrO_2$-8wt%$Y_2O_3$

— Coating sintering determined using dilatometry

— Coating thermal conductivity determined using laser heat-flux technique

— Coating strength and fracture toughness determined using four-point flexure, and asymmetric four-point flexure tests, respectively

# Sintering Shrinkage and Conductivity Test Approaches

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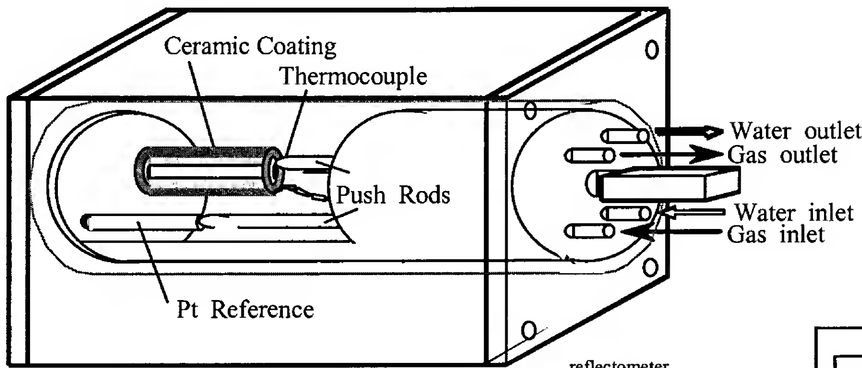
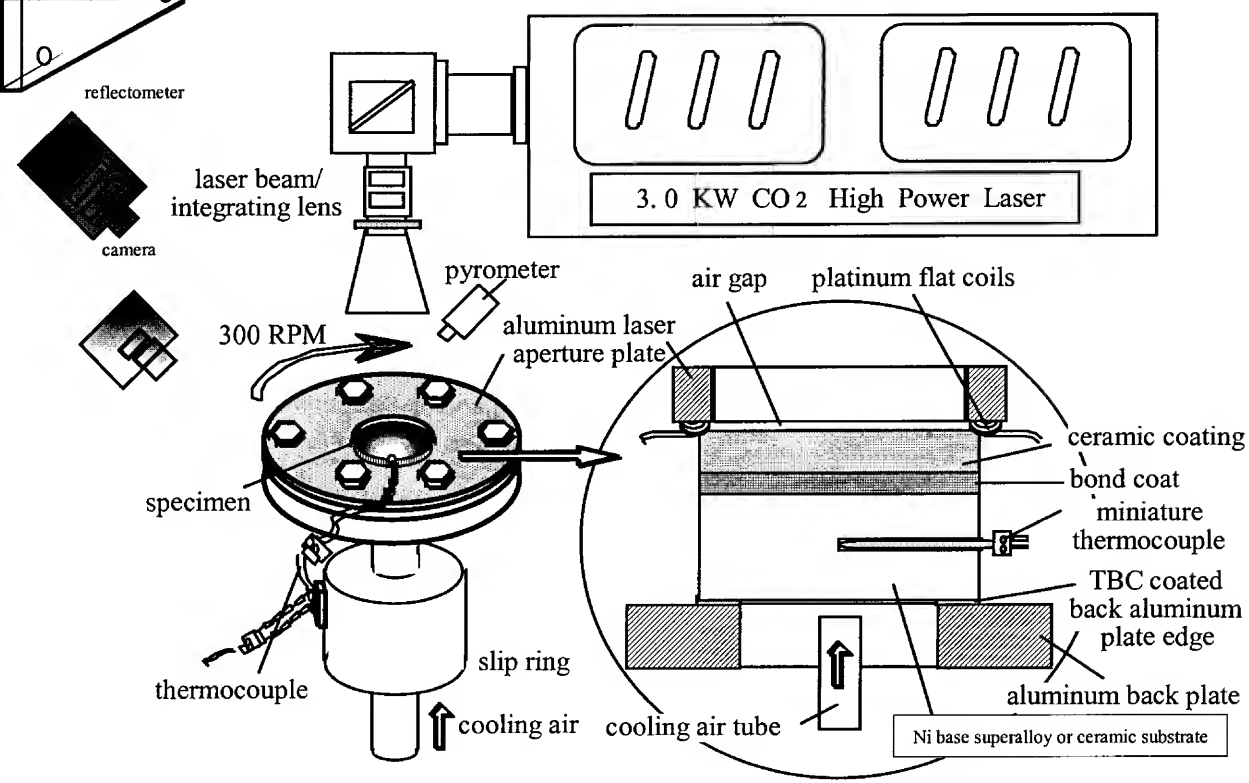
— Dilatometer and laser heat-flux rig for the coating sintering study



# Specimen Configurations

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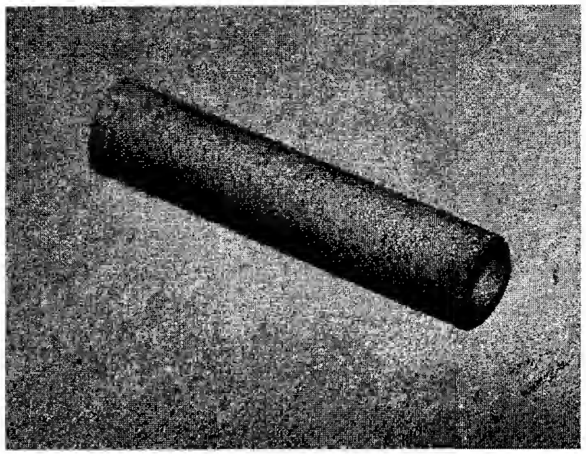
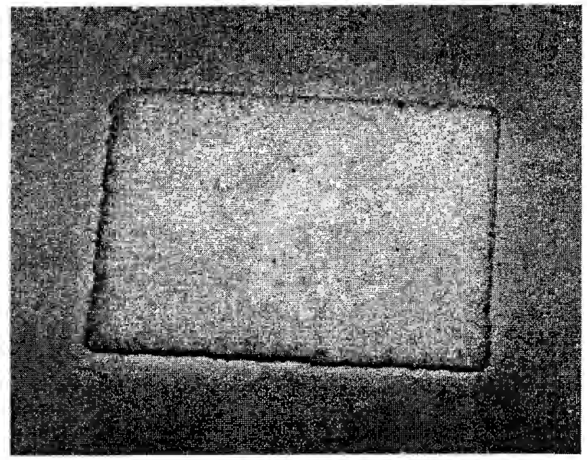
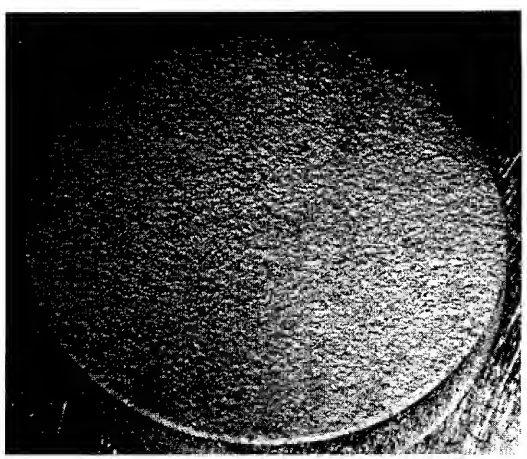
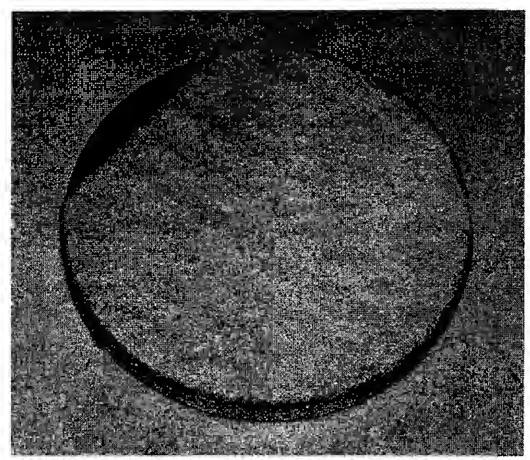
## Dilatometer specimens





## Laser heat flux test specimens





# Specimen Configurations for Mechanical Testing

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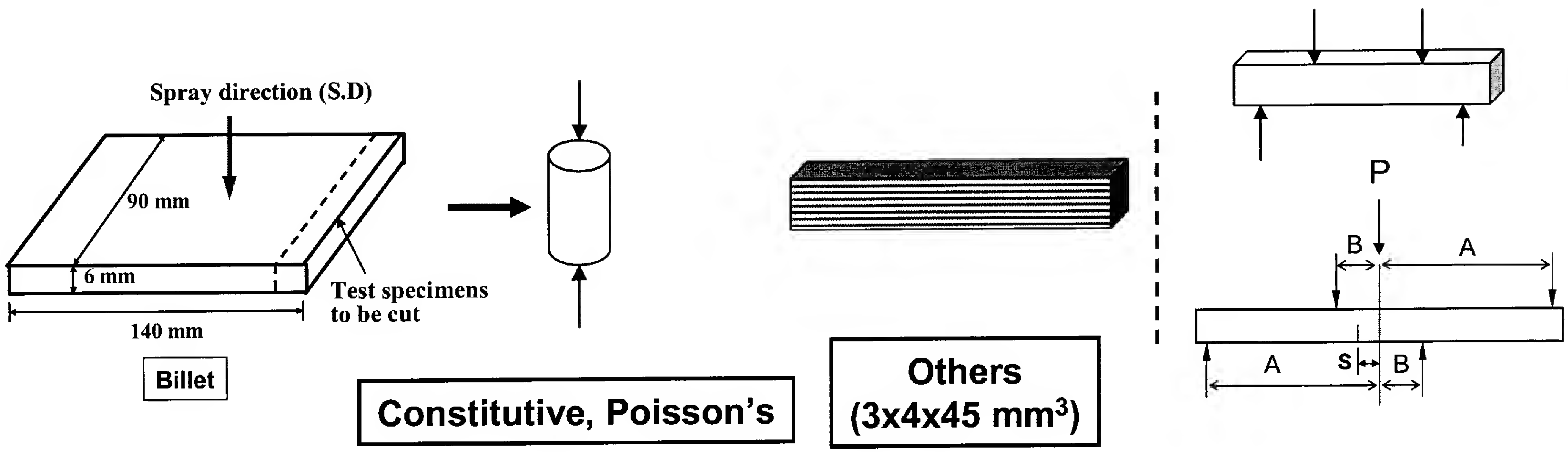
- Sintering Conditions:
  - Temperature/environment: 1316 °C/air
  - Annealing time: 0, 5, 20, 100, and 500 h
- Mechanical & Physical Properties Determined at RT:
  - Flexure strength
  - Elastic modulus
  - Microhardness
  - Phase stability
  - Fracture toughness ($K_{Ic}$ & $K_{IIc}$)
  - Constitutive relation
  - Density
  - Others



# Sintering Behavior of the Plasma-Sprayed $ZrO_2$-8wt%$Y_2O_3$ and Mullite Coatings

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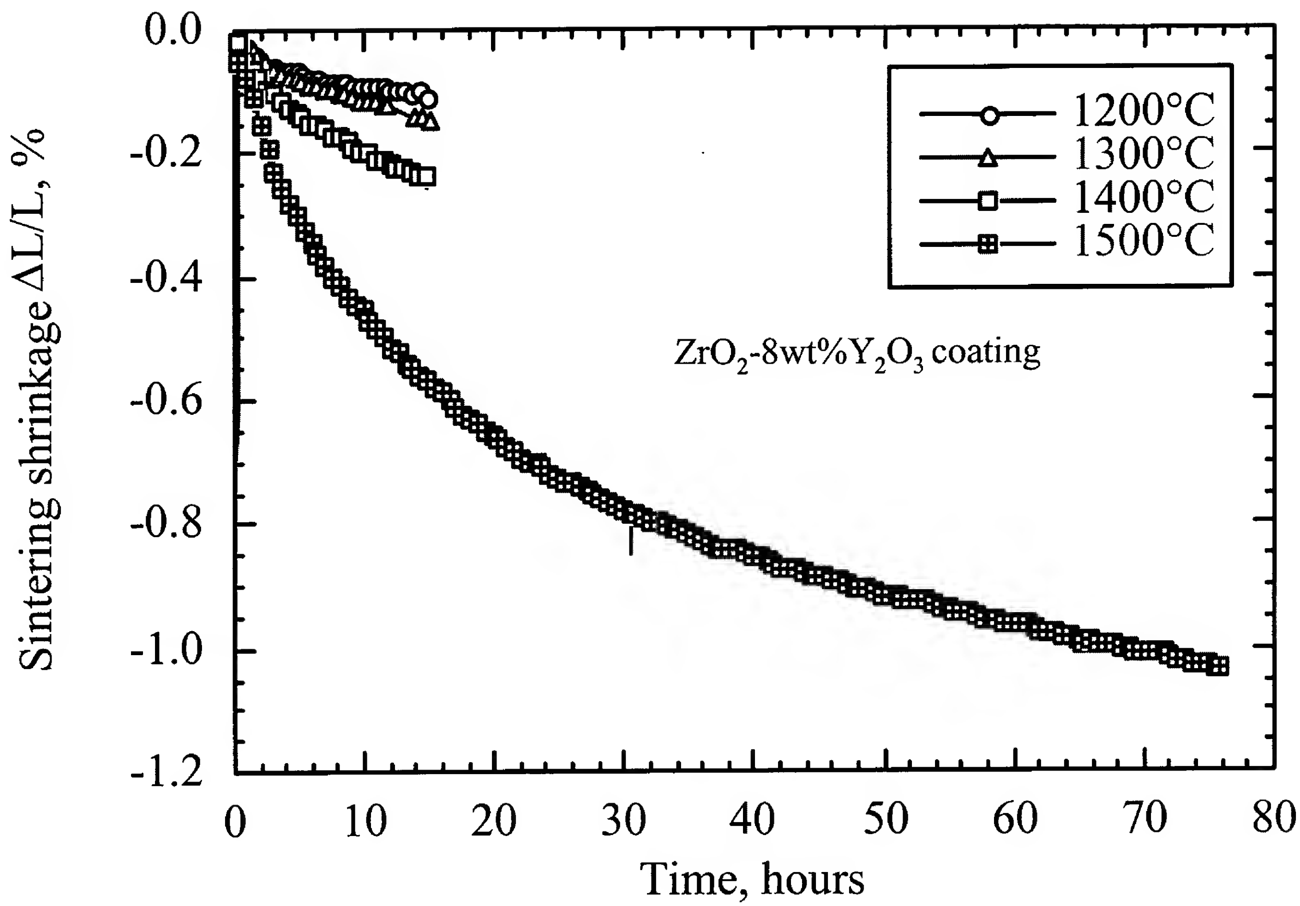
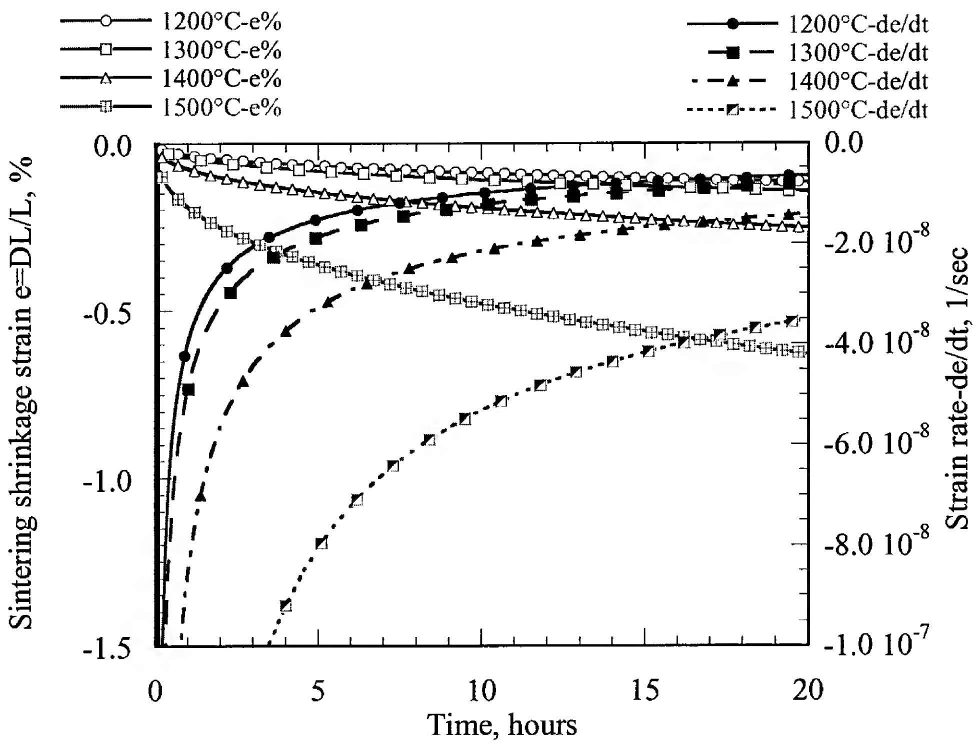
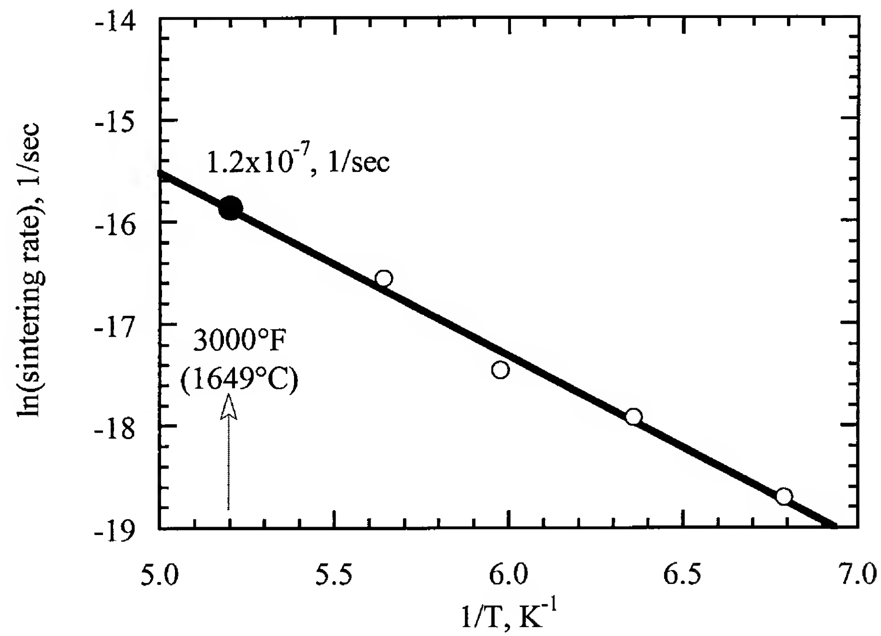
— **Sintering shrinkage as a function of temperature and time determined by a dilatometer**



# Sintering Behavior of the Plasma-Sprayed $ZrO_2$-8wt%$Y_2O_3$ in First 20 Hours

- Sintering shrinkage as a function of temperature and time determined using dilatometer
- Near steady-state sintering rates (5-20 hrs) determined and can be extrapolated to higher temperature regime



# Modeled Sintering Behavior of $ZrO_2$-8wt%$Y_2O_3$ Based on Experiments

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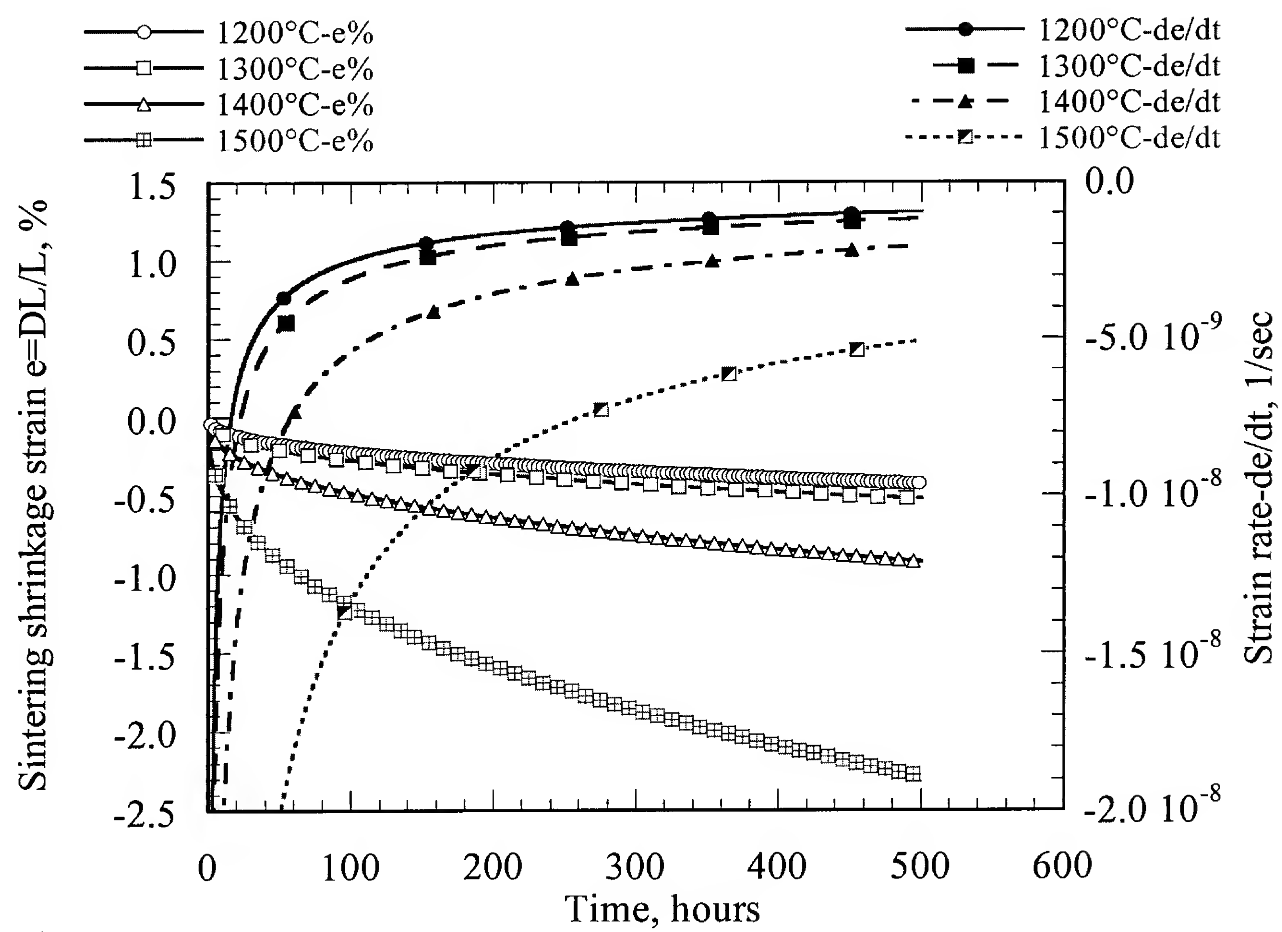
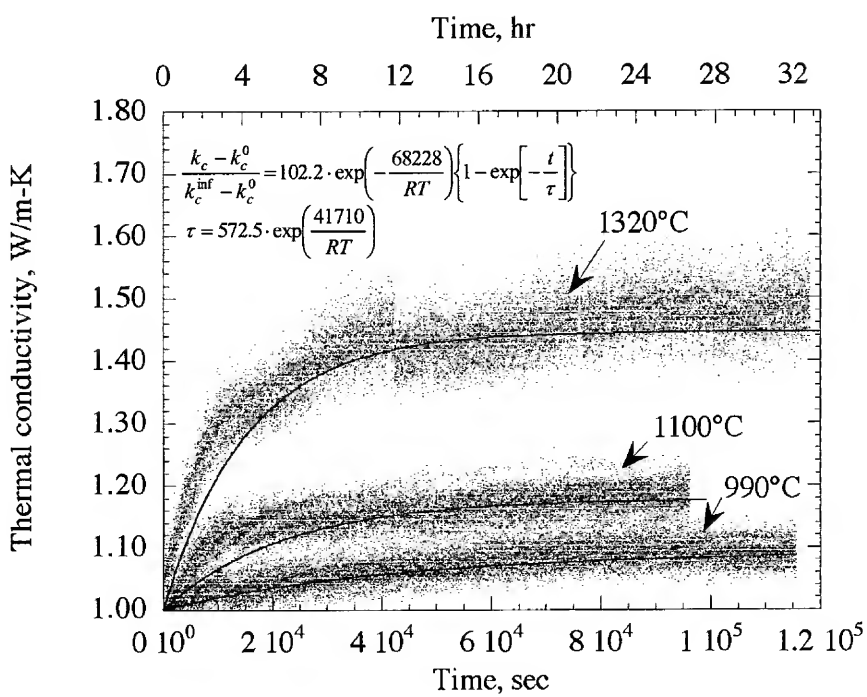
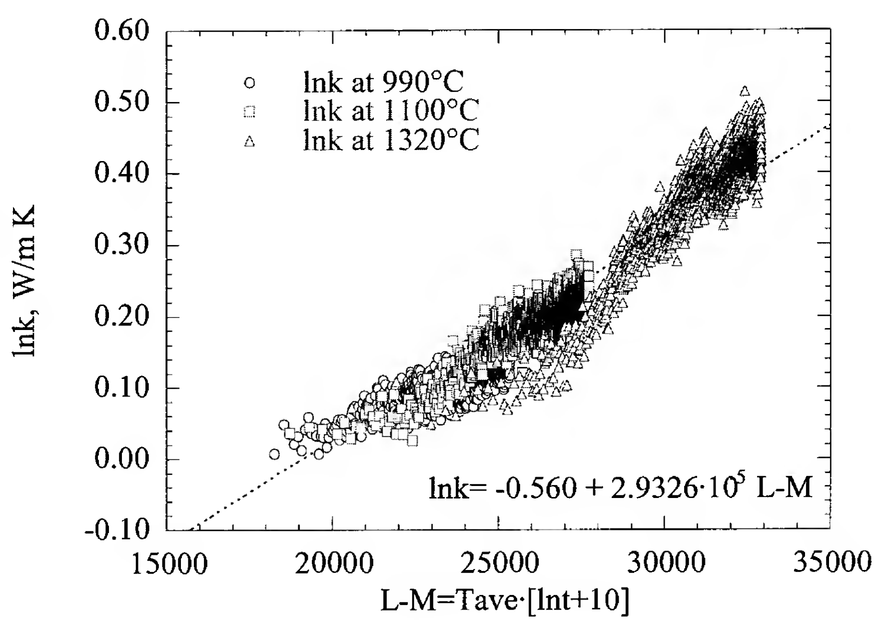
- Model can be used to predict long-term sintering behavior
- Variable sintering rates observed
    - Initial very fast sintering
    - reduced sintering rates with increasing time



# Thermal Conductivity Increase Kinetics of Plasma-Sprayed TBCs under Steady-State Thermal Gradient Testing

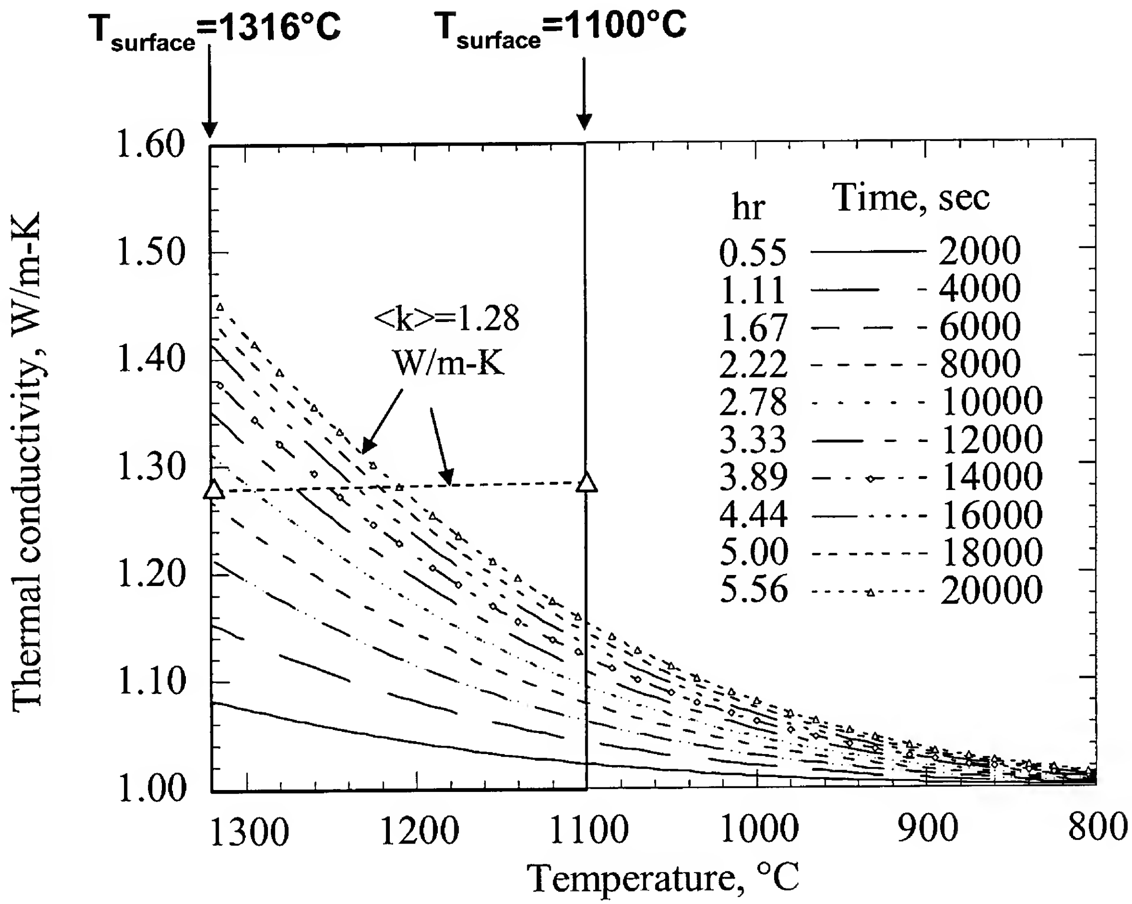
- Thermal conductivity $ZrO_2$-8wt%$Y_2O_3$ as a function of time and temperature at up to 1320°C
- The conductivity reduction by microcracks and micro-porosity can not persist under high temperatures due to coating sintering
- The coating durability can be affected by sintering



# Thermal Conductivity of $ZrO_2$-8wt%$Y_2O_3$ Thermal Barrier Coatings

— **Significant conductivity increase expected with increasing engine operating temperatures**

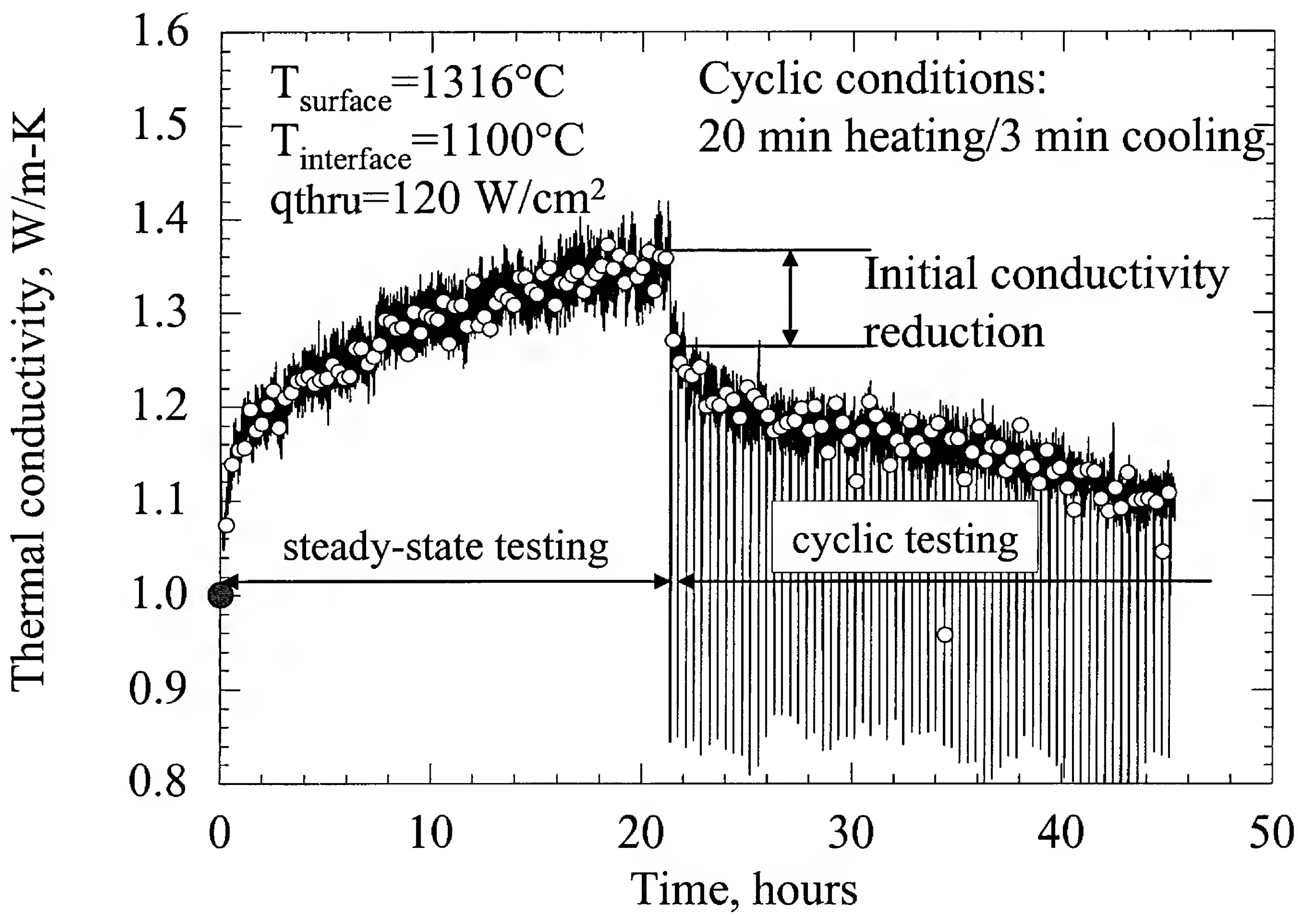



**Time and temperature-dependence of plasma-sprayed $ZrO_2$-$Y_2O_3$ thermal conductivity**

# Thermal Conductivity of $ZrO_2$-8wt%$Y_2O_3$ Thermal Barrier Coatings under Thermal Gradient Testing Conditions



— Sintering induced conductivity increase during ~~the~~ steady-state testing
— Sintered coatings tend to have accelerated delamination under subsequent cyclic testing



# Thermal Conductivity and Sintering of Advanced Multicomponent Low Conductivity TBCs

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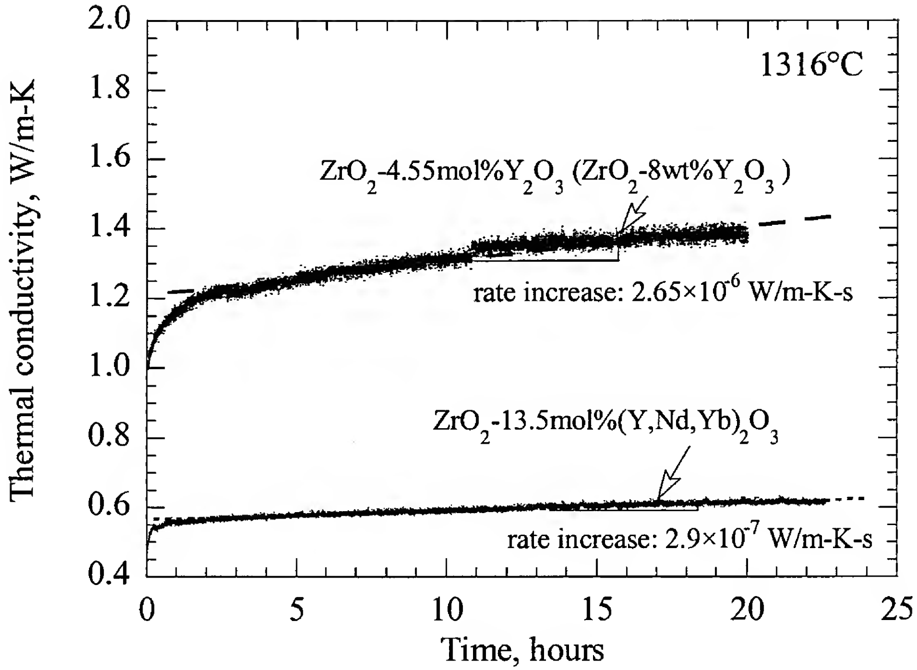
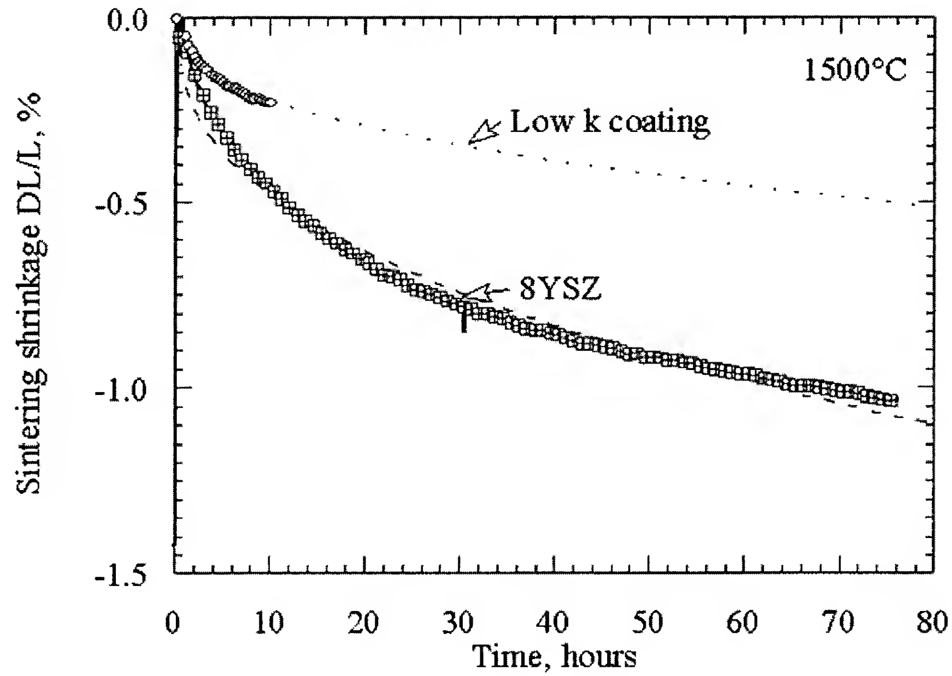
— Sintering and thermal conductivity rate-of-increase significantly reduced at high temperatures for advanced multicomponent thermal barrier coatings due to increased sintering resistance



# Flexure Strength and Fracture Toughness of $ZrO_2$-8wt%$Y_2O_3$

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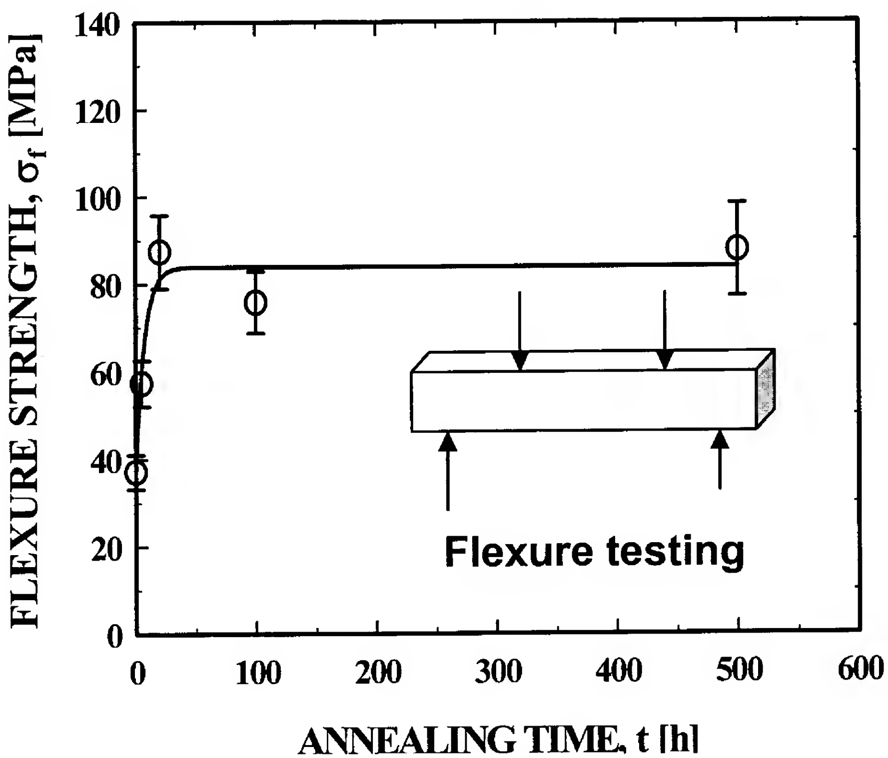
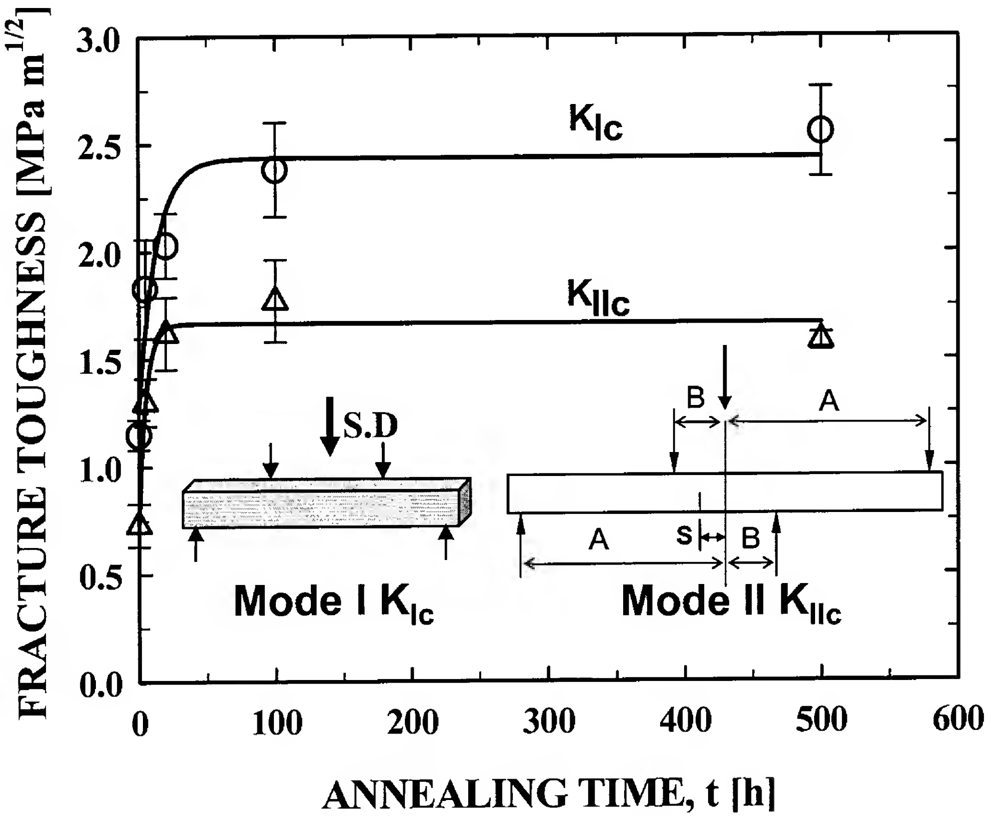
— **Significant increases in flexure strength and fracture toughness due to sintering**




- Significant increase in stength and fracture toughness ($K_{Ic}$& $K_{IIc}$) at $t \leq 20$ h
- Asymptotic at $t > 20$ h, forming a plateau
- Max increase ≥ 220-240 % observed

# Elastic Modulus of Plasma-Sprayed $ZrO_2$-8wt%$Y_2O_3$

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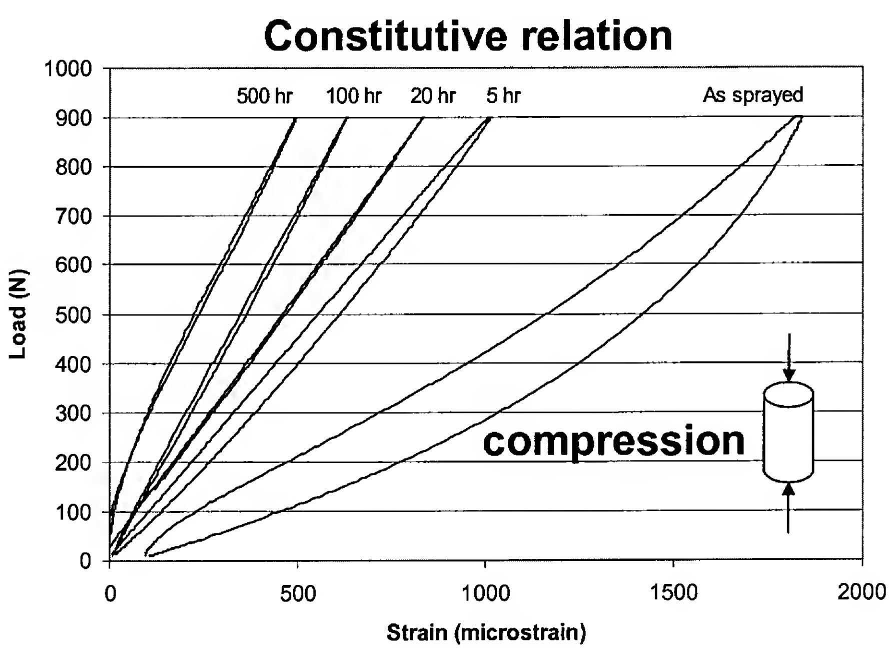
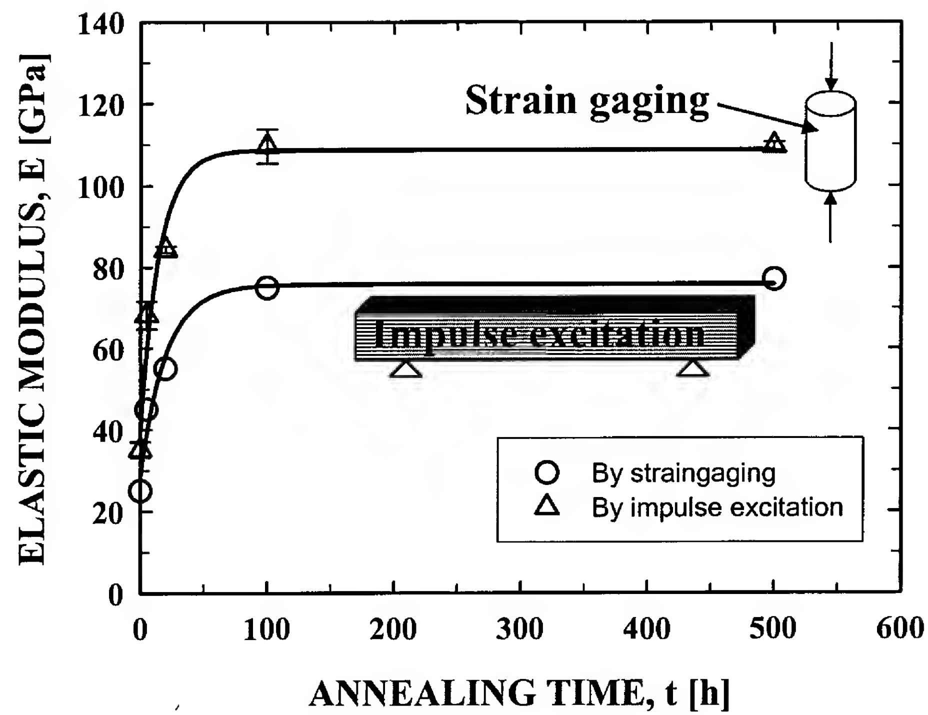
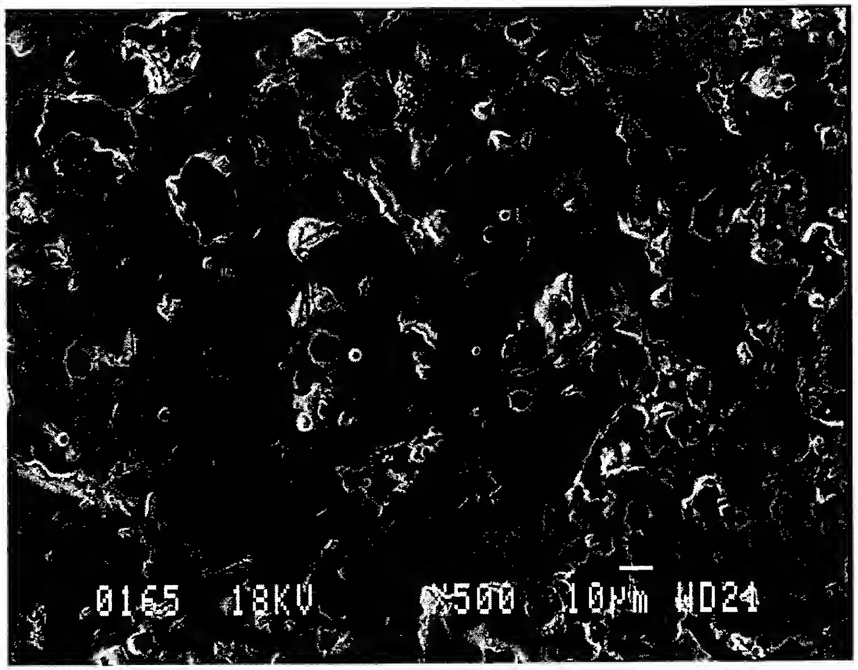
— TBC elastic modulus also increases significantly with annealing/sintering time



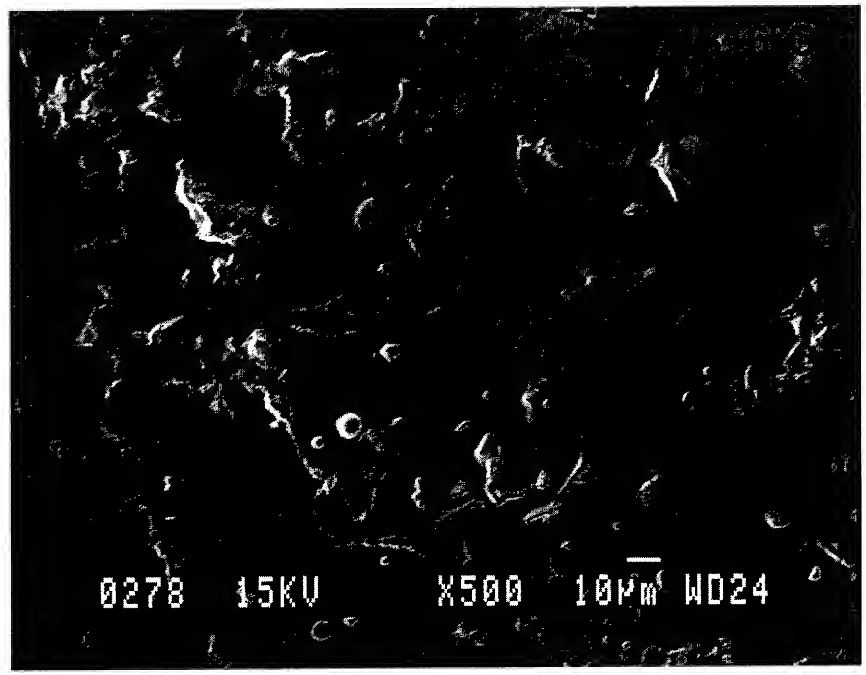




- Significant increase in elastic modulus $t < 100$ h
- Asymptotic at $t \geq 100$ h, forming a plateau
- Max increase in elastic modulus = 300 % for both methods
- Discrepancy in E between two methods

# Effect of Sintering on Microstructures of Plasma-Sprayed $ZrO_2$-8wt%$Y_2O_3$




As-sprayed ($t$=0)




$t$ = 100 h

- As-sprayed – large amount of microcracks and presented
- 100 h annealed – microcracks/micropores healed

# Universal Sintering Map for Plasma-Sprayed Coatings

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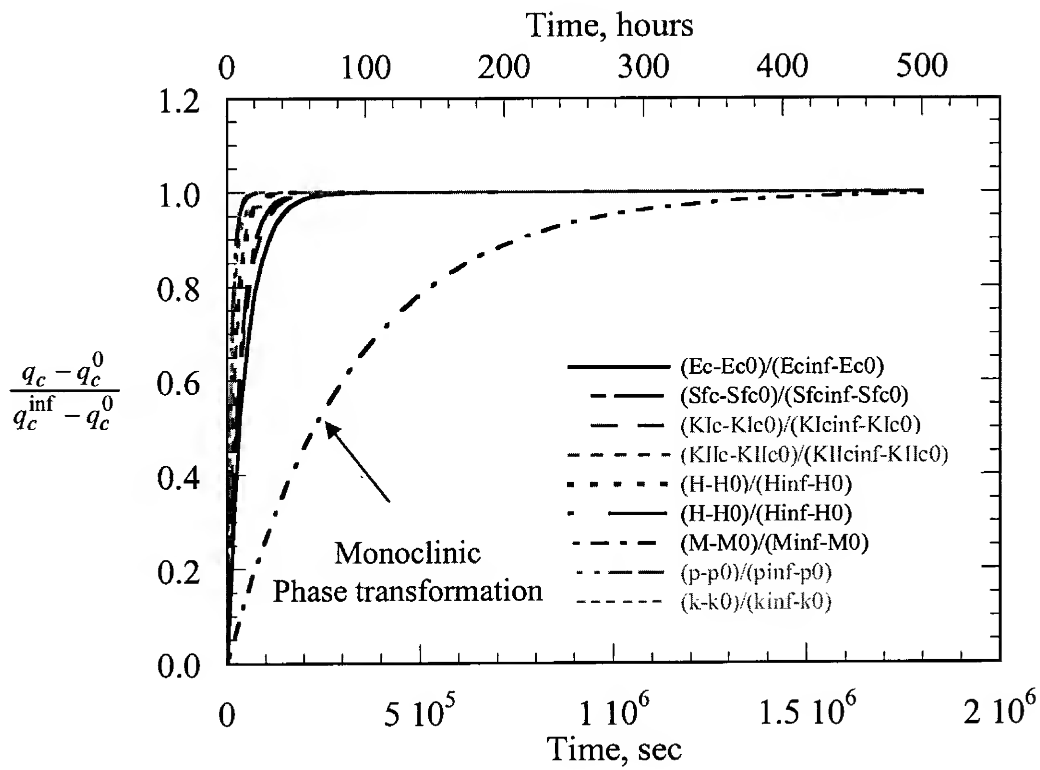
— TBC property changes closely related to coatings sintering phenomenon and kinetics




$$\frac{q_c - q_c^0}{q_c^{inf} - q_c^0} = C \cdot \exp\left((1 - \exp\left(-\frac{t}{\tau}\right)\right)$$

where:

$q_c$ : quantity at time $t$

$q_c^0$ : quantity at $t$=0

$q_c^{inf}$ : quantity at $t$=∞

$C$, $\tau$ : parameters

- Provides a convenient way to determine readily the effect of sintering in terms of its degree between any given properties
- Useful to construct a ‘universal sintering map’

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# Summary

- Dilatometry and laser heat-flux techniques established for coating sintering, thermal conductivity, and durability evaluations
- Sintering effects on fracture toughness and elastic modulus evaluated for as-processed and 1316°C sintering annealed plasma-sprayed coatings
- Sintering behavior of plasma-sprayed $ZrO_2$-8wt%$Y_2O_3$ determined, and Phenomenological Model proposed for a universal sintering map
- Sinter-resistant TBCs desirable for coating strain tolerance and durability
- Advanced coatings show promise to improve high temperature sintering resistance. Mechanical testing also planned for the coating systems

# Acknowledgements

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